

U V - N E A R - I R

FYI

MB 11/27/95

Design and Performance of a Miniature Dual-Beam Diode-Array Spectrometer

J. Thomas Brownrigg
American Holographic, Inc.,
601 River Street, Fitchburg,
MA 01420.

A miniature dual-beam diode-array spectrometer has been developed that operates in four spectral regions from the ultraviolet to the near-infrared. Two spectra, representing the sample and a reference, are dispersed onto a single diode array with a single grating. Measurements of spectral bandwidth, stray light, and sensitivity are described. Examples of instrument operation in the transmission and reflectance modes are presented. The small size of the instrument makes it convenient for on-line or field measurements.

Diode-array spectrometers have become increasingly popular in recent years, largely because of their ability to acquire multiwavelength data very rapidly using no moving parts.

Most commercially available diode-array spectrometers are single beam, although many spectroscopic measurements are dual beam in nature. Examples include transmission and reflectance measurements, or when spectral features of the sample need to be monitored in real-time relative to a reference material. With a single-beam instrument, one must be concerned with light-source variations occurring between measurements, which is much less of a concern when a dual-beam instrument is used.

This article describes the optical design and performance of a miniature dual-beam diode-array spectrometer having moderate (~ 10 nm) spectral resolution and presents examples of transmission and reflectance spectra. Using a novel optical design, a single concave holographic grating disperses light from two slits along a 12.8-mm photodiode array. Two spectra — sample and reference — are thus measured simultaneously. The spectrometer focal distance is 60.8 mm and the f -number is $f/2$. The spectrometer detector, a 256-element photodiode array, includes a 16-bit analog-to-digital (A/D) converter and communications interface to a personal computer. Data can be stored in ASCII file format for subsequent processing. The dimensions of the optical module with A/D converter are 6.5 cm H \times 6.5 cm W \times 14 cm L. Four gratings are available, providing spectral coverage from the ultraviolet (UV) to the near-infrared (near-IR). The spectrometer consists of the MDS optical module and the diode-array detector with associated electronics.

OPTICAL MODULE

The MDS optical module is cylindrical, with the grating at one end and the two slits and detector at the opposite end. Figure 1 shows a side view of the module. Light enters the two slits and then passes through glass filters located behind the slits. The purpose of these filters is explained below. After passing through the filters, the light strikes the grating and is dispersed and focused onto the diode array.

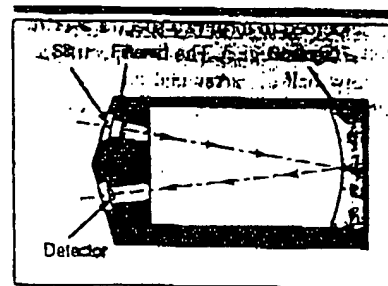


Figure 1. Side view of the MDS optical module.

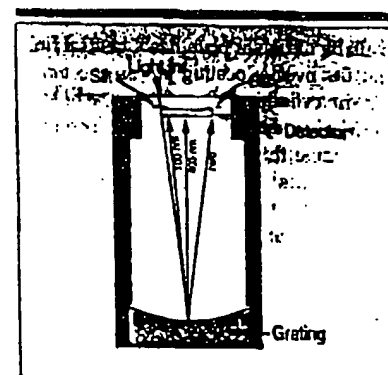


Figure 2. MDS optical schematic showing wavelength distribution over the diode array.

BEST AVAILABLE COPY

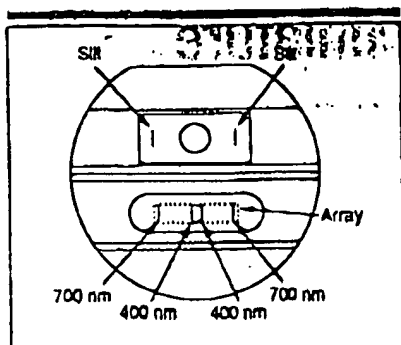
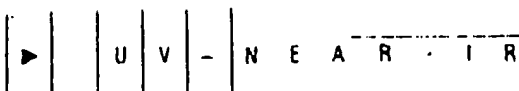


Figure 3. Slit and detector view of the MDS optical module.

Figure 2 is a schematic diagram showing the dispersion of light from one of the slits. In this figure, the positive first-order spectrum from the left slit is dispersed over the array. The zero-order light (undispersed) is imaged off the array. Light of wavelengths shorter than 400 nm (for the "color" version of the module) is absorbed by the glass filter located behind the slit. Light entering the other slit is dispersed in the opposite direction along the array, and a second filter behind this slit absorbs the shorter wavelengths. Therefore, white light entering both slits is dispersed to form two spectra over the 400–700-nm region. The two spectra each occupy half the array and have opposite dispersion. Figure 3 is a schematic diagram of the slit and detector end of the module showing the location of the two spectra with respect to the array. The unused negative first-order and higher-order light strikes the spectrometer wall, which is covered with a strongly absorbing black material.

The standard spectrometer slit plate has two $100\text{-}\mu\text{m} \times 2.5\text{-mm}$ slits; slit dimensions of $100\text{-}\mu\text{m} \times 1.0\text{-mm}$, $50\text{-}\mu\text{m} \times 1.0\text{-mm}$, and $50\text{-}\mu\text{m} \times 2.5\text{-mm}$ are also available. The slit plate has a central hole that fits over a locating pin on the body, and the cylindrical glass filters are held in the MDS body by the slit plate. The optical module thus consists of three optical components: the grating, which is cemented into the body, and two glass filters. There are no moving parts and no adjustments, except for initial positioning of the detector.

The spectrum of a low-pressure mercury lamp obtained with the color version of the MDS is shown in Figure 4. Note the approximate mirror symmetry about the array center; the symmetry is not perfect because the intensity of the light

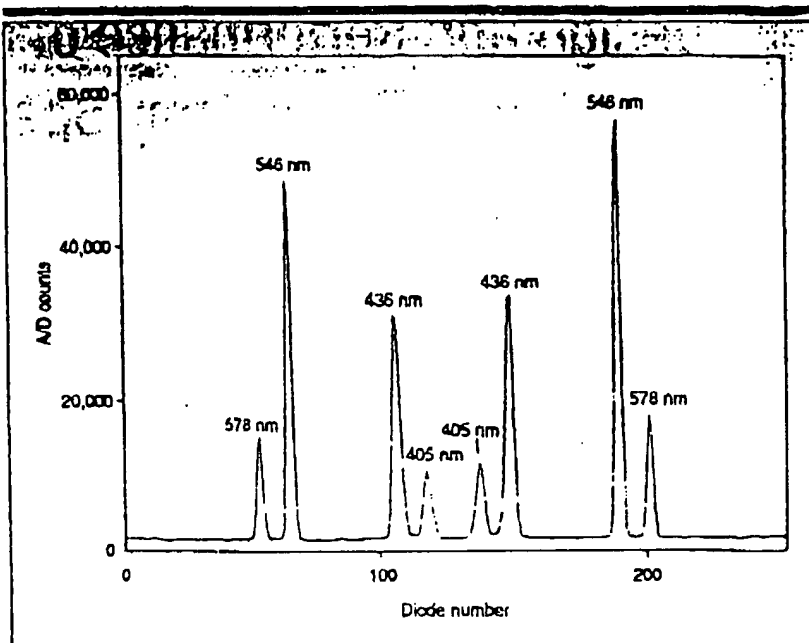


Figure 4. Spectrum of a low-pressure mercury lamp obtained with the MDS color spectrometer.

entering the slits is generally not equal, and small differences in grating illumination may exist between the two paths.

DETECTOR AND ELECTRONICS

The main restriction on the choice of detector is that its overall length is about 13 mm (or less), since the slit separation is 13.8 mm. Thus, 256-element silicon photodiode arrays having diodes on $50\text{-}\mu\text{m}$ centers, or 512-element arrays with diodes on $25\text{-}\mu\text{m}$ centers, can be used. Examples are the EG&G (Sunnyvale, CA) types RL0256TB and RL0512SB and Hamamatsu (Hamamatsu City, Japan) types S3921-256Q and S3924-512Q. We presently use an EG&G RL0256TBU detector, which has 256 elements on $50\text{-}\mu\text{m}$ centers. The array is used without a cover plate to reduce stray light resulting from internal reflections within the plate; transmission in the short wavelength UV is also improved. The detector socket is mounted on a small circuit board with two holes on either side. Two screws hold the detector board to the MDS body. The mounting holes are slightly oversize to permit some lateral adjustment (centering) of the detector.

The EG&G detector is interfaced to an A/D converter (16 bit, 10 MHz), which mounts on top of the MDS module. The A/D board microprocessor communicates with a host interface box (HIB),

which communicates with an IBM-compatible personal computer. Evaluation software, written in C, enables the user to quickly obtain data at different integration times and formats. The data can be saved to ASCII files and exported into other programs for further processing. For example, we use LabCalc software (Galactic Industries, Salem, NH) for spectral analysis.

WAVELENGTH CALIBRATION

The demonstration software includes a program for wavelength calibration using linear regression (least squares) analysis. An analysis of the wavelength distribution using the grating equation shows that assuming a linear relationship between diode position and wavelength results in a maximum error of $\sim 2\text{ nm}$ over the 380–730-nm wavelength range. Additional errors, of course, arise from the uncertainty in the slopes and intercepts derived using linear regression. An analysis of these errors suggests that, if the diode positions are determined to ± 0.1 pixel, the uncertainty in the wavelengths obtained from linear regression on four calibration lines is 1–2 nm. This is of the same magnitude as the departure of the calibration curve from linearity. Therefore, it appears that even if more calibration lines were used, the accuracy would be no better than about $\pm 1\text{ nm}$. Better ac-

U V - N E A R

I

R

curacy should be possible using a polynomial with quadratic or cubic terms or both.

We typically use low-pressure mercury or argon lines for calibration. Light from these lamps is coupled to the spectrometer slits using glass or optical quartz fiber optics. Wavelengths that have been found useful for MDS calibration are given in Table I.

SPECTRAL LINE WIDTH MEASUREMENTS

The usual definition of spectral resolution is given by the Rayleigh criterion. According to this criterion, two lines of equal intensity are resolved if there is valley of ~20% between the two peaks (1). In practice, however, it is difficult to find spectral line pairs whose separation is such that the Rayleigh criterion is satisfied. For this reason, we have used a different operational definition. We define the spectral line width as follows: The spectral line width or bandwidth is the width (in nanometers) of a monochromatic spectral line measured at half-intensity with respect to the adjacent spectral background. It is important that this line be "monochromatic," or as free from interferences as possible. Thus, the spectral line width is defined here as the full width at half-maximum (FWHM) intensity of a monochromatic line.

As noted previously, there are four slits available for the MDS. Spectra of a low-pressure mercury lamp were obtained with an MDS color version having each of these slits. A glass bifurcated fiber optic coupled the lamp housing to the slits. A piece of ground glass between the lamp and the input to the fiber optic was used to attenuate and diffuse the light. Line width measurements are summarized in Table II.

From the table it is clear that the line widths obtained for 50- μ m slits are nearly the same as those obtained for 100- μ m slits. For the color version of the MDS, the spectral bandwidth is 2.73 nm/diode. Therefore, the most intense portion of a monochromatic line image occupies ~3 diodes. If there were no aberrations of the slit images, the image of a 100- μ m slit should occupy ~2 diodes since the pixel width is 50 μ m. It appears that aberrations thus limit the bandwidth to ~10 nm, and that the effective image width is ~150 μ m for either a 50- μ m or 100- μ m slit. The maximum MDS spectrometer f -number is $f/2.0$. If the f -number were made larger, the image

Table I. Lines of the low-pressure mercury (Hg) and argon (Ar) lamps useful for MDS wavelength calibration.

Spectral region	Lamp	Wavelength (nm)
UV	Hg	253.7, 296.7, 312.9 (312.6/313.2), 334.2
Visible	Hg	404.7, 435.8, 546.1, 578.0 (577.0/579.1)
Near-IR	Ar	696.5, 763.5, 912.3, 965.8

quality should improve because of reduced astigmatism, with a corresponding reduction in line width. The limiting image width would then be the pixel width, which for this detector is 50 μ m. If a 50- μ m image were obtained, the image could occupy at most 2 pixels, or an apparent image width of 100 μ m. The corresponding minimum line width would thus be ~5.5 nm.

Line widths were measured in a similar fashion for the UV, clinical, and near-IR versions of the MDS. For the UV and clinical versions, a mercury lamp was used, whereas an argon lamp was used for the near-IR version. The MDS slit in all cases was 50 μ m \times 2.5 mm. A bifurcated fiber optic — optical quartz for the UV and glass for the visible and near-IR — coupled the source to the MDS. The ferrules of the fiber optic were positioned ~5 mm from the slits. The line width measurements are summarized in Table II. The estimated uncertainties in the line width measurements range from ± 0.5 nm for the UV version to ± 1.5 nm for the near-IR version.

WAVELENGTH RANGES

To determine the wavelength ranges of the MDS, a mercury or argon lamp was coupled to the slits using a glass or quartz bifurcated fiber optic. The MDS slits were 50 μ m \times 2.5 mm. The MDS was equipped with the appropriate glass filters and detector described previously.

Wavelength calibration was performed using linear regression. The required input for each line is the wavelength and the location of the peak in terms of diode number. Although the peak diode number can be estimated to within ± 0.5 diode from an inspection of the saved spectral data file, better accuracy was achieved by examining the data file in LabCalc.

Table II. Mean spectral line widths and standard deviations of atomic lines measured with the MDS.

Version	Slit	Mean width (nm)	SD (nm)
Color	50 μ m \times 1 mm	8.5	2.1
	50 μ m \times 2.5 mm	7.9	1.1
	100 μ m \times 1 mm	9.1	2.0
Clinical	100 μ m \times 2.5 mm	8.4	1.1
	50 μ m \times 2.5 mm	6.9	1.3
UV	50 μ m \times 2.5 mm	2.9	0.7
Near-IR	50 μ m \times 2.5 mm	13.6	4.6

Lines measured:

Color: Hg 404.7, 435.8, 546.1, 578 (unresolved doublet)

Clinical: Hg 365.2 (unresolved triplet), 404.7, 435.8, 546.1, 578.0

UV: Hg 253.7, 296.7, 312.9, 334.2

Near-IR: Ar 696.5, 763.5, 912.3, 965.8

Table III. Measured wavelength ranges for the MDS modules.

Model	Range (nm)	Estimated uncertainty (nm)
UV	190–360	± 5
Clinical	330–630	± 10
Color	380–730	± 10
Near-IR	580–1100	± 15

feature of LabCalc, which was actually designed for chromatography, can be used to obtain peak maxima to approximately ± 0.1 diode. The wavelength ranges using the calibration data are summarized in Table III.

The spectral ranges given in Table III do not include the possible effect of the filter glasses used in the MDS. The calculated transmission of the glasses used in the clinical and color versions are ~50% at the shortest wavelengths given in Table III. The filter used in the near-IR version, however, has ~5% transmission at 580 nm, and ~50% at 590 nm.

STRAY LIGHT

Stray light was measured using glass filters, which are essentially opaque at the wavelength of interest, but transmit at longer wavelengths. The 50-mm square \times 3-mm thick filters selected were from

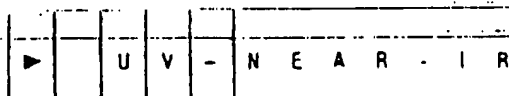


Table IV. Stray light ratios for the color MD5 using tungsten (W), deuterium (D₂), and xenon (Xe) lamps.

λ (nm)	W	W + KG5 filter	D ₂	Xe
400	0.1	0.02	1×10^{-3}	2×10^{-3}
500	0.01	2×10^{-3}	6×10^{-4}	1×10^{-3}
600	6×10^{-3}	4×10^{-4}	5×10^{-4}	1×10^{-3}

A Schott publication (2) giving transmission characteristics was obtained from the manufacturer. Filters used and the measurement wavelengths were: GG475 (405 nm), OG550 (500 nm), RG645 (600 nm), RG780 (700 nm), and RG1000 (800 nm). All of these filters except RG1000 had an internal transmittance of $<10^{-5}$ at the measurement wavelength; for RG1000 the transmittance was 5×10^{-5} .

Both tungsten-halogen (40-W) and deuterium (30-W) lamps were used for stray light measurements. The lamps were in a common housing that was part of a model 139 Perkin-Elmer (Norwalk, CT) spectrophotometer. The aperture of the lamp housing was imaged onto the single-bundle end of a Dolan-Jenner Industries (Lawrence, MA) glass bifurcated fiberoptic bundle, and the two legs of the fiber optic were attached to an adapter near the MD5 slits.

To measure the stray light, the spectrum of the lamp was obtained without a filter in place. A Schott filter was then installed and the filter spectrum recorded. Finally, light was blocked and a "dark" spectrum was obtained. Data were saved to an ASCII text file and exported to LabCalc for manipulation and display. The spectrum of the low-pressure mercury lamp was obtained to establish wavelength calibration. The stray light ratio (SLR) is defined as the ratio of the intensity of the source with a filter installed to the intensity without a filter at the measurement wavelength (dark signals subtracted); the smaller the ratio, the lower the amount of stray light relative to desired light. It should be emphasized that the stray light measured in this manner is total (integrated) stray light at wavelengths longer than the measurement wavelength.

In most instances a similar set of measurements was obtained including a Schott KG5 filter (3-mm thick) with the cut-off filters. This filter removes most of the light beyond ~ 850 nm. SLRs for the color version of the instrument are given

in Table IV. From Table IV, SLRs using a deuterium lamp are $\sim 10^{-3}$; the ratios are about the same with or without a KG5 filter. The SLRs are much greater for a tungsten lamp unless a KG5 filter is used. The improvement in SLRs using the KG5 filter is due to the prevention of most of the near-IR light from entering the instrument. This light can scatter from the grating and other surfaces, thus contributing to stray light. In addition, silicon detectors are particularly sensitive to near-IR light up to ~ 1100 nm. For these reasons, the use of a KG5 filter or similar near-IR-absorbing filter is recommended when using a tungsten lamp in the visible region.

More recently, stray light was measured for the color MD5 using a 10-W xenon flash lamp (EG&G FX280). These data are included in Table IV. Data shown in this table were obtained without the use of a KG5 filter; however, the KG5 filter further reduces stray light by factors of two to four.

SLRs obtained for the near-IR version with the tungsten lamp were 2×10^{-3} (600 nm), 7×10^{-4} (700 nm), and 4×10^{-4} (800 nm). The measurement uncertainties in the SLRs are quite large due to the very small signal (nearly at the dark level) associated with the filter measurement. These uncertainties range from $\sim 100\%$ in the visible region to $\sim 300\%$ in the near-IR region.

SENSITIVITY

Instrument sensitivity is defined here as the minimum detectable signal (when the signal is three times the noise) of an MD5 color optical module with the EG&G RL0256TBU diode-array detector and electronics. To measure sensitivity, the MD5 spectrometer was mounted on an optical bench having a 40-W tungsten lamp. Two pieces of ground quartz were placed over the exit aperture of the lamp housing for attenuation and improved image uniformity. A quartz lens with an attached iris diaphragm focused the rectan-

gular lamp aperture onto the slit. The iris diameter and lens focal distance were adjusted to give an input f -number of 2.0, thus matching the spectrometer f -number.

Irradiance measurements at specific wavelengths were obtained with four interference filters positioned near the lamp: 420 nm, 521 nm, 525 nm, and 650 nm. The filter bandwidths ranged from ~ 12 nm to 22 nm. A neutral density filter (density 3.0) was placed in the optical path to further reduce the intensities of light transmitted through the filters.

The MD5 was temporarily removed from the optical bench and in its place was positioned a calibrated silicon detector (Model 818-ST, SN404, Newport, Irvine, CA). The detector surface was positioned at the location of the MD5 slit. The detector size was 10 mm \times 10 mm and was therefore much larger than the physical size of the image. The detector photocurrents for each filter were measured using a Keithley (Cleveland, OH) Model 417 picoammeter. Three or four measurements were taken with each filter in place, and then with the light through the filters blocked. The "dark" signals from residual ambient light were subtracted from the filter signals.

After the above measurements were made, the MD5 spectrometer was returned to the optical bench with one slit at the position previously occupied by the Newport detector. The same interference filters (with neutral density filter) were again measured and the data stored to ASCII-format files. These data files, consisting of the signals in A/D counts and diode number, were imported to LabCalc for further analysis and display. Also stored were the background (dark) measurements, which were then subtracted from each filter spectrum.

MINIMUM IRRADIANCE AT SLIT

The average photocurrents for the four filters and the Newport detector sensitivities are summarized in Table V. Also included in this table are the measured signal-to-noise ratios (S/Ns) with a neutral density 3.0 (ND3) filter positioned after the interference filters. S/Ns are with dark counts subtracted. Spectral bandwidths of the filters (FWHM intensities) are also given.

The following is a sample calculation of the minimum spectral irradiance at the

U V - N E A R - I R

Table V. Experimental data for estimating MD5 spectrometer sensitivity. Detector photocurrents are without the ND3 filter in place. The minimum irradiances (S/N = 3) are given in the last column.

Filter (nm)	Detector responsivity (A/W)	Detector current (μA)	Filter bandwidth (nm)	Signal/noise (with ND3)	Minimum irradiance (pW/cm ² nm)
420	0.2295	0.240	21.5	24.6	25
521	0.3167	0.329	12.4	52.4	20
525	0.321	0.770	11.6	132	20
650	0.4128	1.17	13.2	131	21

MD5 slit for the 525-nm filter. The power incident on the Newport detector with the ND3 filter in place is (from Table V):

$$\frac{0.770 \times 10^{-6} \text{ A} \times \text{W}}{0.321 \text{ A} \times 10^{-3}} = 2.40 \times 10^{-9} \text{ W} \quad [1]$$

Since the image area is $4 \text{ mm} \times 6 \text{ mm} = 0.24 \text{ cm}^2$, the calculated spectral irradiance is:

$$\frac{2.40 \times 10^{-9} \text{ W}}{(0.24 \text{ cm}^2 \times 11.6 \text{ nm})} = 8.62 \times 10^{-10} \text{ W/cm}^2 \text{ nm} \quad [2]$$

The corresponding S/N of the filter band corresponding to this irradiance is 132. For a S/N = 3 (a reasonable estimate of detectability) the scaled irradiance is $1.96 \times 10^{-11} \text{ W/cm}^2 \text{ nm}$, or $19.6 \text{ pW/cm}^2 \text{ nm}$. Calculated minimum irradiances at the four wavelengths are given in Table V.

These estimates of sensitivity may be

used to determine whether the amount of light available to the instrument will provide adequate signal to noise. This assumes one knows the power of the incident source, the fraction of power transmitted or reflected by the sample, and losses due to transfer optics. We have used these estimates to predict the instrument sensitivity for measurement of quinine sulfate fluorescence; agreement with the experimental value was within a factor of two.

APPLICATIONS

Principal applications for dual-beam spectrometry are transmission (absorption) and reflectance measurements. As an example of a reflectance measurement, several colored ceramic tiles were measured using a 10-W xenon flash lamp (EG&G FX280U). The flash lamp was mounted vertically in a stand with two fiberoptic bundles in proximity to the lamp enve-

lope. A sampling accessory supported two fiberoptic bundles close to the sample surface. Light from the lamp was conducted through the fiberoptic bundle to the sampling accessory, and was directed normal to the sample surface. Light reflected from the sample surface was collected at 45° by the other fiber bundle and carried to the spectrometer slit. There were two such sampling accessories, one for the sample (colored) tile and the other for a reference (white) tile. All fiber bundles were optical grade fused silica (Dolan-Jenner Industries).

Figure 5 shows spectra of the xenon lamp obtained in reflectance from a white ceramic tile, for both sample and reference. The vertical axis is in units of A/D counts. An MD5 color version was used for these measurements. The wavelengths for the two spectra vary from $\sim 380 \text{ nm}$ near the center of the array to $\sim 730 \text{ nm}$ at the ends of the array (compare with the spectrum of the mercury lamp in Figure 4). Figure 6 shows the ratio of these same two spectra, with signals interpolated to specific wavelength increments using the wavelength calibration data. The irregular line is the ratio spectrum using the spectra of Figure 5; the irregularities are due to calibration errors and small optical differences in the two spectra. This spectrum can be stored and used as a correction factor for subsequent ratio data. The result of dividing a ratio scan by this stored correction factor gives the nearly straight line in Figure 6.

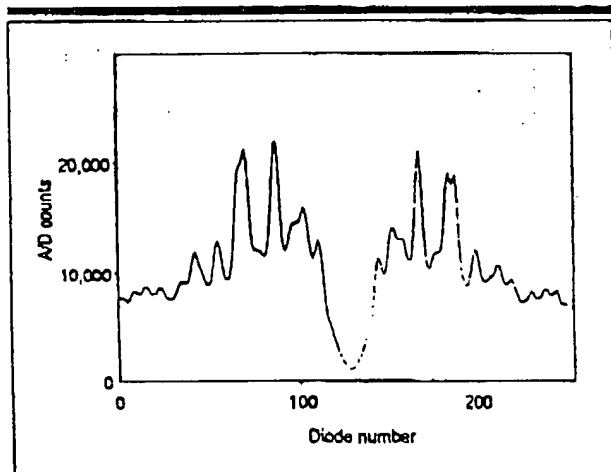


Figure 5. Spectrum of a xenon flash lamp measured in reflectance from a white ceramic tile.

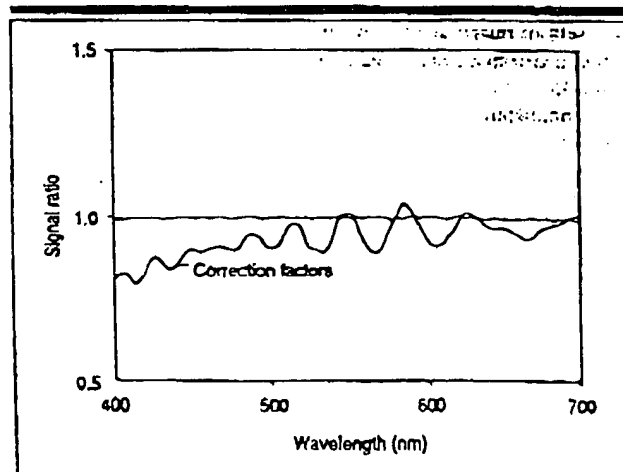


Figure 6. Spectrum of a xenon flash lamp reflected from a white tile in ratio mode. The irregular line is the ratio spectrum using the spectra from Figure 5, which can be used as a correction factor. The straight line results from dividing a ratio scan by this stored correction factor.

U V - N E A R - I R

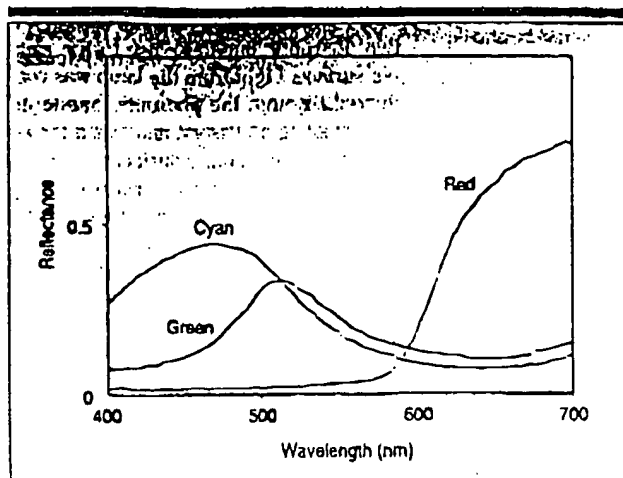


Figure 7. Reflectance spectra of colored ceramic tiles measured relative to a white tile.

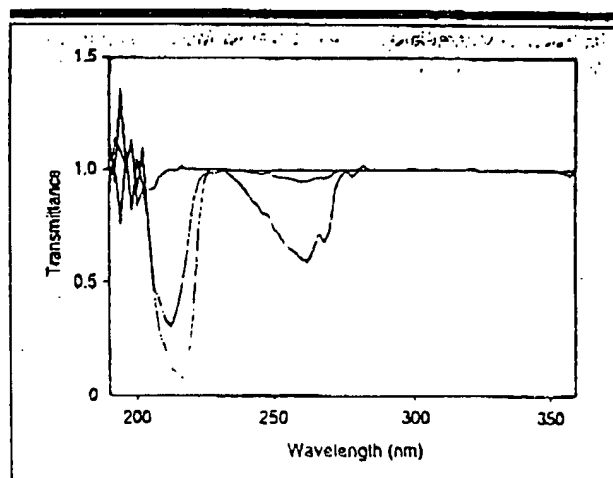


Figure 8. Transmission spectra of toluene in methanol v. methanol (concentrations 0, 10, and 100 ppm) using a xenon flash lamp.

Figure 7 shows the spectra of several colored tiles, using the stored correction factor as a divisor. All spectra were measured relative to a white tile. The spectra show the expected higher reflectance associated with the color of the tile; for example, the peak reflectance near 700 nm is for the red tile. All data were obtained with a single flash of the xenon flash lamp, for which the pulse-to-pulse variation was 0.5–1% root mean square (RMS).

Transmission measurements are more appropriate if the sample is transparent in the wavelength region of interest. A dual-beam measurement fixture designed for use with a xenon flash lamp consisted of two aluminized plane mirrors and two sets of quartz lenses to direct light through two fused silica cells (1-cm path length).

Transmittance spectra of toluene in methanol using the UV version of the MD5 is shown in Figure 8. The main features of the spectra agree with a published spectra in hexane (3); the published spectra shows three absorption maxima at ~189, 208, and 262 nm. The spectra obtained here is distorted at short wavelengths because of solvent absorption and other optical losses below ~225 nm. The baseline RMS noise for single flashes of the lamp is about 1%. Data from multiple flashes could be averaged for lower noise.

For the above examples, the sample was measured relative to a white surface or pure solvent. However, with a dual-beam spectrometer the reference material can be whatever is relevant to the mea-

surement. For example, for a color measurement the reference could be a sample of the material with "acceptable" color characteristics. Similarly, the transmission of an organic liquid or polymer film could be referenced to that of a similar material having the desired properties.

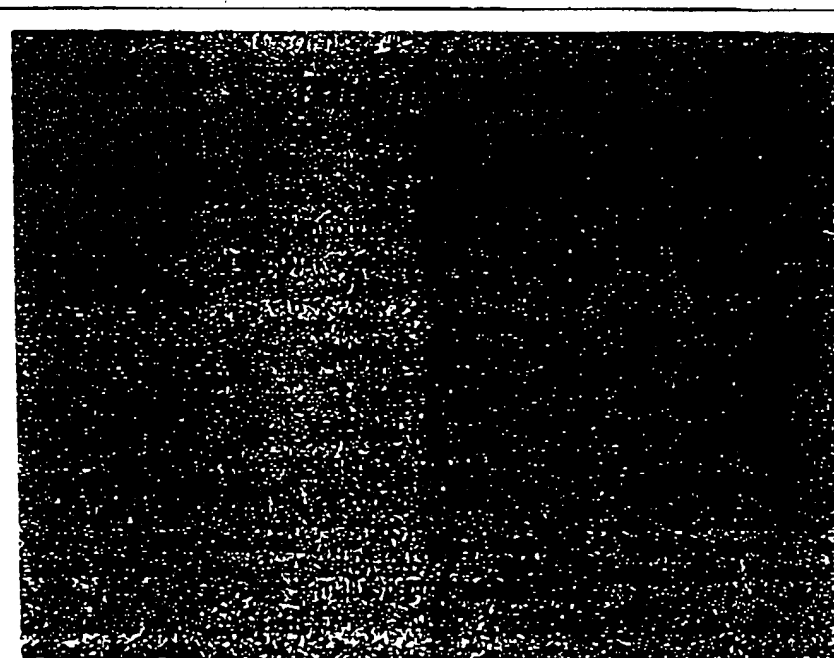
ACKNOWLEDGMENTS

The author thanks Charles S. Hatch, optical engineer, and Raymond Merkh, mechanical engineer, for their contributions to the design and construction of the

measurement fixtures. Andrew Xiang made significant improvements to the software. Selma Johnson provided invaluable service in preparation of the manuscript.

REFERENCES

- (1) R. A. Sawyer, *Experimental Spectroscopy*, (3rd Ed., Dover, New York, 1963), p. 36.
- (2) *Optical Glass Filters* (Schott Glass Technologies, Duryea, PA), 1984.
- (3) *DMS Atlas of Organic Compounds*, Vol. 1 (Plenum, New York, 1966), p. D2/1. ♦



**This Page is Inserted by IFW Indexing and Scanning
Operations and is not part of the Official Record**

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☒ **BLACK BORDERS**
- ☐ **IMAGE CUT OFF AT TOP, BOTTOM OR SIDES**
- ☒ **FADED TEXT OR DRAWING**
- ☒ **BLURRED OR ILLEGIBLE TEXT OR DRAWING**
- ☒ **SKEWED/SLANTED IMAGES**
- ☒ **COLOR OR BLACK AND WHITE PHOTOGRAPHS**
- ☐ **GRAY SCALE DOCUMENTS**
- ☐ **LINES OR MARKS ON ORIGINAL DOCUMENT**
- ☐ **REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY**
- ☐ **OTHER:** _____

IMAGES ARE BEST AVAILABLE COPY.

As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.